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The research carried out under this contract investigated the electronic properties of small semiconductor devices where transport is dominated or affected by quantum phenomena. This has importance both for the future application of small devices and the understanding of the physics of these structures. Topics investigated included small silicon MOS transistors, here it is shown that large, intrinsic, stresses affect transport in the two dimensional inversion layer. As the stress is at the edge of the device, it is not significant for larger structures.
The electron-phon interaction in epitaxial layers of GaAs has been investigated using Schottky gate FETs (MESFETs) here it is shown that the nature and interpretation of magnetophonon oscillations is strongly affected by the geometry of the sample. Studies of small samples were extended to one dimensional GaAs-AlGaAs heterojunctions where it was shown that varying the width at low temperatures resulted in large random conductance fluctuations, these were fitted to the appropriate theory. next page ..../cont

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~~Finally~~, a description is given of measurements and analysis of electronic transport in MBE grown InSb, supplied by Dr J Dinan and Mr I Golding at Night Visition Laboratory, Fort Belvoir. → Keywords: → to field 8

The report section and list of publications resulting from this contract covers the 3 year period and it is not necessary to refer to the interim or previous annual reports.

QUANTUM PHENOMENA IN SEMICONDUCTOR STRUCTURES

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Abstract

The research carried out under this contract investigated the electronic properties of small semiconductor devices where transport is dominated or affected by quantum phenomena. This has importance both for the future application of small devices and the understanding of the physics of these structures. Topics investigated included small silicon MOS transistors, here it is shown that large, intrinsic, stresses affect transport in the two dimensional inversion layer. As the stress is at the edge of the device, it is not significant for larger structures.

The electron-phonon interaction in epitaxial layers of GaAs has been investigated using Schottky gate FET's (MESFET's), here it is shown that the nature and interpretation of the magnetophonon oscillations is strongly affected by the geometry of the sample. Studies of small samples were extended to one dimensional GaAs-AlGaAs heterojunctions where it was shown that varying the width at low temperatures resulted in large random conductance fluctuations, these were fitted to the appropriate theory.

Quantum corrections to the conductivity and Hall effect were investigated in a range of III-V semiconductors, and, in a new development, a technique of electrostatic squeezing was developed to investigate quantum interference in a ring of electron gas in a GaAs-AlGaAs heterojunction.

Finally, a description is given of measurements and analysis of electronic transport in MBE grown InSb supplied by Dr J Dinan and Mr T Golding at Night Vision Laboratory, Fort Belvoir.

The report section and list of publications resulting from this contract covers the 3 year period and it is not necessary to refer to the interim or previous annual reports.

Report

Silicon gate MOS devices with a width 0.6 - 0.8μm have been used to study electron transport in the 2D electron gas of the Silicon inversion layer. The results of the application of uniaxial stress were compared with results obtained using large width devices (50μm). It was clear that the inbuilt stress at the edges of the device affected the entire channel of the narrow transistor. The large edge stresses result in a mixing of the heavy and light mass valleys with a consequently lower mobility than in the stress free case. The effect of applied stress on quantum interference has shown that this process is modified as electrons can occupy both the heavy and light mass subbands simultaneously. Quantum interference causes the conductivity to reduce as the temperature decreases and is cut off by the application of a magnetic field. The effect of the magnetic field is reduced by stress induced intervalley scattering compared to the case of large devices. Possibly, the stress arises during oxide growth during fabrication and may be reduced by

differing oxidation and annealing treatments.

In view of the high level of interest in small samples exploiting the 2D electron gas in GaAs-AlGaAs heterojunctions, we investigated one dimensional transport in this system. A split gate Schottky gate FET was fabricated which allowed the progressive reduction in width of a high mobility 2D electron gas. The conductivity temperature relation was investigated and interpreted in terms of quantum interference and interaction effects. Theoretical analysis showed that the energies of the one dimensional quantised levels could be determined by the application of a magnetic field. This increased the energy of the subbands resulting in structure in the conductivity as each individual level passed through the Fermi energy. This structure occurred at different values of magnetic field to the Landau level (Shubnikov-de Haas) oscillations occurring in a wide 2D electron gas. Calculations showed that the location of the quantised level was in agreement with a parabolic confining potential.

In a further series of experiments, the conduction of a split gate structure was measured at low temperatures as a function of width. Large random fluctuations in conductance were imposed on a smooth variation. These are the "Universal Conductance Fluctuations" found previously in small systems as a function of Fermi energy or magnetic field. Its origin is in quantum interference between electron waves scattered around a loop in different directions. As the sample becomes small, the distribution of loops becomes a discrete, rather than a smooth function of size. Changing the width of the sample, when the phase coherence length is greater than the width, alters the contribution of the loops in a different, but random, way. The magnitude of the fluctuations is reduced by phase incoherence and can be considered as arising from resistors in series, each of which has length equal to a phase coherence length. The results of this analysis showed that the phase coherence length was due to electrons being scattered from fluctuations in charge, a mechanism unique to one dimension.

The interaction between electrons and optical phonons was investigated using GaAs Schottky gate FET's - utilising epitaxial GaAs rather than heterojunction material. Sweeping a magnetic field results in the observation of structure in the conductivity when optical phonon energy equals the separation of two magnetic levels. However, it was found that the phase and amplitude of the resulting magnetophonon oscillations was determined by sample geometry. This resulted in differences when the magnetic field was either parallel or perpendicular to the current flow. A model was developed for the analysis of the results which was in good agreement with experiment.

New structures utilising GaAs-AlGaAs heterojunctions were developed as part of this programme. A combination of photo-resist and metal was used to produce a ring of 2D electron gas of approximate diameter 10^{-4}cms with a variable width in the range 3.10^{-5} to 5.10^{-6}cms. This represented an advance on previous ring structures which had been formed by etching or ion

implantation. Interference took place between electron waves traversing the two arms and then recombining, the extent of the interference oscillated with magnetic flux - the Aharonov-Bohm effect - and was investigated in detail. Evidence of interference was also found between electrons which completely traversed the loop but in different directions. The amplitude of the oscillations was up to about 20%, a very high value indicating that an optimisation of the structure may result in other aspects of interference being determined.

Report on Indium Antimonide

This section describes the results obtained on electronic properties of Indium Antimonide/Cadmium Telluride heterostructures. The heterostructures were supplied by the Night Vision and Electro Optics Laboratories, Virginia, USA and were grown by Mr T D Golding and Dr J Dinan. These measurements are continuing and manuscripts are being prepared. Further results will be discussed in future reports on the new E.R.O. Grant DAJA45-C-0011 "Physics Related to Future Electronic Devices".

Fabrication of Samples

The heterostructures were supplied as pieces of MBE grown Cadmium Telluride (CdTe) grown epitaxially on Indium Antimonide (InSb) substrates. Some of the samples had an InSb spacer layer grown on the substrate followed by the CdTe.

The first step was to prepare Hall bars to enable resistance measurements to be made. A Hall bar pattern was defined using photoresist , and then the samples were etched in one of 2 etchants, either 1:2:2 $HNO_3 : H_2O_2 : H_2O$ for 5 seconds or 1:1:2 $HNO_3 : H_2SO_4 : H_2O$ for 30 seconds. Weaker, and hence slower etches, fail to reliably etch away the surface layer.

Contacts

For samples fabricated into 2mm x 0.5 mm Hall bars with contact pads ~0.7 mm in diameter small (~0.3mm) dots of indium were placed on the surface and annealed for 10 minutes at 180°C. Then 50μm diameter gold wire was pressed into the dots at a temperature of 110°C when the indium becomes slightly soft. This method produced very good contacts with resistances typically less than 0.1Ω at 4.2K.

For samples etched into really small Hall bars and for use at high magnetic fields (>2T) this was impractical and AuGeNi contacts were used. The standard recipe used for Gallium Arsenide was tried and found to work, i.e. 2000Å of an alloy made up of Gold, Germanium and Nickel. Leads were then attached using a Kulick and Soffa Gold wire bonder.

Some of the samples were not etched at all. Four dots of indium were attached, one at each corner.

This was done to check for parallel conduction in the substrate, since this could give very strange results in etched samples. The Van der Pauw technique was used for getting resistance and Hall resistance from these samples.

Experimental

The characterisation of these samples were done on a continous flow cryostat, because of its speed and convenience. The characterisation had to be done at less than 10K because the substrates conduct above this temperature. The Hall voltage and Magnetoresistance were measured as a function of magnetic field over the range 0 to 1.2 T. The Hall resistance gives the carrier concentration and hence the mobility of these samples could be obtained.

Most of the early samples had very poor electrical propeties, although normally appearing good by materials criteria. By feeding back, to Fort Belvoir, the results obtained much better quality samples have been produced lately. The problems faced are listed below. Some typical mobilities are listed in the table below.

i) **Substrate conduction**

Many of the substrates used were excessively good conductors. The results obtained from etched samples were meaningless, and unetched samples merely showed the effects of conduction in bulk InSb. Samples grown on these substrates were completely useless for electrical measurements and are not included in the table.

ii) **Samples with buffer**

All the samples grown with an Indium Antimonide buffer layer had a large number of electrons per square metre. These electrons are almost certainly sitting in the metallic buffer layer which is in these samples more conducting than the 2D electron gas. This is because the buffer layer has too many defect sites to be an insulator. This is in turn a result of the very small number of impurities required for metallic behaviour in InSb, less than 10^{14} cm^{-2} compared with about 10^{16} in GaAs. Therefore, all the working samples were grown without the buffer layer. This inability to use modulation doping is the most important cause of the mobilities in these samples not being as high as in conventional GaAs heterostructures, and is certainly the main problem that will have to be solved before this materials system can rival GaAs.

iii) **Excessive numbers of electrons.**

Other samples without the buffer layer were also found to have too many electrons to be a good 2D gas. This may be due to a number of effects. One possibility is that these samples may have a layer of Indium at the interface, or the samples may just have a poor quality interface with lots of defects.

iv) Heat Treatment Growth Temperature and Pressure Optimisation.

Once the gross causes of samples to fail electrically had been eliminated, there was still variation in sample parameters. Preliminary results from a controlled sequence of samples varying substrate cleaning method, growth temperature and pressure of Cadmium used suggest that Auger sputtering is of no use for cleaning substrates intended for electrical use, even though it produces better surfaces as shown by microscopy or SIMS. The Auger sputtering process introduces too many electrical scatterers. Also low growth temperatures appear to help, along with high Cadmium growth pressure.

v) Too few electrons

It is now possible to grow good electrical interfaces in this materials system. However, once all the causes of excessive defects are eliminated, another problem emerges. There are no longer enough electrons for a high mobility 2D gas. Since the mobility μ varies with carrier concentration as $\mu \propto n^{3/2}$ having a low carrier concentration results in a low mobility. The way round this problem in the future will be to dope the Cadmium Telluride some way from the interface to increase the number of electrons (modulation doping).

The best sample is number 090288C It shows a mobility of 22 000 $cm^2V^{-1}s^{-1}$ at 4.2K with a low carrier concentration of only 2.0×10^{11} cm^{-2}. This is much better than the best previously reported and since $\mu \propto n^{3/2}$ this represents a very significant increase in interface quality.

Physical Results - Quantum Hall Effect and Magnetoresistance

Those samples which worked were investigated in a number of other ways, in a variety of cryostats, over temperatures from 4.2K down to 300 mK and at fields of up to 8T.

The Quantum Hall effect occurred in the highest mobility sample. The plateaux in the Hall effect were accurately quantised to 1% and good zeroes of resistance were seen. Only one period of oscillation is seen ,and the plateaux at higher field are flat. This is conclusive proof that there is only one subband of the 2D electron gas occupied in this sample.

Low field magnetoresistance experiments in both parallel and perpendicular field were made which give information about inelastic and spin flip scattering in these samples. The inelastic time fits standard weak localisation theory for an electron gas typically of order 1000Å thick for those samples that had a high 2D electron density, and for a 2D gas for samples 090288C and 012788B. This suggests that only in the last two samples, has a conclusive 2D electron gas been achieved. This is expected for a narrow gap semiconductor because the low mass means that a second subband is occupied at lower carrier concentrations than in other common materials such as GaAs.

The spin flip scattering time was also measured. Conventional theories give poor results but spin flip scattering at impurities in a narrow band gap semiconductor gives a reasonable fit to experiment.

The temperature dependence of resistance was measured, and with the magnetoresistance this should have given an estimate of the strength of interactions. However the temperature dependence had the wrong sign, which means that there is something unusual happening in these samples, probably causing resistance changes through another process.

Conclusion

InSb - CdTe heterostructures have been characterised and many problems associated with making of good electronic interfaces have been solved.
The major success has been the demonstration of a good 2D gas in this system.
The remaining problems are growing a good InSb buffer, of doping CdTe and of inverse growth of InSb on CdTe so as to use CdTe substrates which are insulating at room temperature.
If these are solved then the system should approach its intrinsic potential of a very high mobility system, because of the low mass. This materials system is almost certainly worth pursuing, in view of the eventual possibility of integrated optics with night vision detectors.

TABLE

SAMPLE NO.	Carrier density / cm^{-2}	Mobility/cm^{2}V^{-1}s^{-1} At 4.2K	Notes
033087C	6.4×10^{11}	1890	
033087G	1.2×10^{12}	3010	
071087B	1.25×10^{13}	6450	
071087C	1.09×10^{12}	270	n estimate unreliable due to localisation
071087D	5.95×10^{14}	3200	
012788B	1.22×10^{11}	10200	
012788C	1.14×10^{12}	3150	
012788D	3.75×10^{12}	2760	
083088A	3.9×10^{12}	6470	

083088B	1.9×10^{11}	640	n estimate unreliable due to localisation
090288C	2.03×10^{11}		21100
090888D	2.55×10^{11}		9800

Papers published as part of this Contract

1. "Magnetic Depopulation of 1D Subbands in a Narrow 2D Electron Gas in a GaAs-AlGaAs heterojunction", K-F Berggren, T J Thornton, D J Newson and M Pepper, Phys. Rev. Lett. 57, 1769, 1986.
2. "Universal Conductance Fluctuation and Electron Coherence Lengths in a Narrow 2D Electron Gas", T J Thornton, M Pepper, H Ahmed, G J Davies and D Andrews, Phys. Rev. B36, 4514, 1987.
3. "Quantum Corrections to the Hall Effect in III-V Semiconductors", D J Newson, M Pepper, E Y Hall and G Hill, J. Phys. C20, 4369, 1987.
4. "Magnetophonon Effect in GaAs Schottky Gate Field Effect Transistors", T P C Judd, M Pepper and G Hill, Appl. Phys. Lett. 53, 54, 1988.
5. "The Aharonov-Bohm Effect in Electrostatically Defined Heterojunction Rings", C J B Ford, T J Thornton, R Newbury, M Pepper, H Ahmed, C T Foxon, J J Harris and C Roberts, J. Phys. C21, L325, 1988
6. "Intrinsic Stress in Narrow Silicon Metal-Oxide-Semiconductor Field Effect Transistors: Magnetotransport Measurement", N Paquin, M Pepper, A Gundlach and A Ruthven, Appl. Phys. Lett. 53, 198, 1988.
7. "Negative Magnetoresistance in Uniaxially Stressed Si(100) Inversion Layers", N Paquin, M Pepper, A Gundlach and A Ruthven, Phys. Rev. 38, 1593, 1988
8. "Electron Magnetotransport in Uniaxially Stressed Si(100) Inversion Layers", N Paquin, M Pepper, A Gundlach and A Ruthven, Submitted to J. Phys. C.
9. "Experimental Determination of Large Intrinsic Edge Stresses in Narrow Silicon Structures", N Paquin, M Pepper, A Gundlach and A Ruthven, submitted to J. Phys. C.
10. "Temperature Dependence of the Conductivity in Uniaxially Stressed Si Inversion Layers at Low Temperatures", N Paquin, M Pepper, A Gundlach and A Ruthven, submitted to J. Phys. C.
11. "Electron-Electron Scattering in Narrow Si Accumulation Layers", D M Pooke, N Paquin, M Pepper and A Gundlach, submitted to Physical Review.

5. Abstracts of Papers Published

1) **Magnetic Depopulation of 1D Subbands in a Narrow 2D Electron Gas in a GaAs:AlGaAs Heterojunction**

K.-F. Berggren,[a] T. J. Thornton, D. J. Newson, and M. Pepper[b]
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(Received 12 May 1986)

We present results on the transverse magnetoconductance in the range 0.3 to 8 T of a narrow, variable-width channel in a GaAs:AlGaAs heterojunction. As the width of the channel is decreased below 0.25 μm the structure in the magnetoconductance changes from Shubnikov–de Haas oscillations to the magnetic depopulation of one-dimensional subbands. A semiclassical WKB calculation is presented which gives good agreement with experiment.

PACS numbers: 72.20.My, 73.40.Lq

2) **Universal conductance fluctuations and electron coherence lengths in a narrow two-dimensional electron gas**

T. J. Thornton, M. Pepper,* and H. Ahmed
Cavendish Laboratory, Cambridge CB3 OHE, United Kingdom

G. J. Davies and D. Andrews
British Telecom Research Centre, Martlesham, Ipswich, United Kingdom
(Received 27 January 1987; revised manuscript received 19 May 1987)

The conductance of a narrow two-dimensional electron gas in a GaAs:$Al_{0.3}Ga_{0.7}As$ heterojunction fluctuates as a function of magnetic field. The variance and correlation length of the fluctuations have been measured for a number of temperatures, and the electron phase-breaking length is found to vary as a small negative power of the temperature.

3) **Quantum corrections to the Hall effect in III–V semiconductors**

D J Newson†, M Pepper‡, E Y Hall§ and G Hill§
† Cavendish Laboratory, Cambridge University, UK
‡ Cavendish Laboratory, Cambridge University, UK, and GEC Hirst Research Centre, East Lane, Wembley, UK
§ Department of Electrical Engineering, University of Sheffield, Sheffield, UK

4) **Magnetophonon effect in GaAs Schottky gate field-effect transistors**

T. P. C. Judd and M. Pepper
Cavendish Laboratory, University of Cambridge, Cambridge CB3 OHE, United Kingdom
G. Hill
Department of Electrical Engineering, The University of Sheffield, Mappin Street, Sheffield S10 2TN, United Kingdom

(Received 9 March 1988; accepted for publication 28 April 1988)

We have investigated the magnetophonon resonance in lightly doped GaAs Schottky gate field-effect transistors of different shape. It is shown that the phase and amplitude of the observed oscillations are dependent upon geometrical considerations. A model is presented in good agreement with experiment.

5) **The Aharonov–Bohm effect in electrostatically defined heterojunction rings**

C J B Ford†, T J Thornton†, R Newbury†, M Pepper†, H Ahmed†,
C T Foxon‡, J J Harris‡ and C Roberts‡
† Cavendish Laboratory, Cambridge CB3 0HE, UK
‡ Philips Research Laboratories, Redhill, Surrey RH1 5HA, UK

Received 3 February 1988

Abstract. Micrometer-sized loops of two-dimensional electron gas have been made on GaAs–AlGaAs heterostructures by electrostatic confinement. A split gate is used to define the loop, allowing the width of the conducting channels to be varied by changing the gate voltage. The magnetoresistance has been measured at low temperatures ($T < 100$ mK) and shows strong Aharonov–Bohm oscillations with amplitudes of up to 7% of the total resistance in the narrowest devices. The oscillations are strong out to $B \approx 0.5$ T and then die out as B increases to ≈ 1 T, with a possible dependence on the channel width. Magnetic depopulation of the 1D sub-bands is also seen.

6) **Intrinsic stress in narrow silicon metal-oxide-semiconductor field-effect transistors: Magnetotransport measurements**

N. Paquin and M. Pepper
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A. Gundlach and A. Ruthven
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(Received 22 March 1988; accepted for publication 20 May 1988)

Measurements of the Hall (ρ_{xy}) and transverse (ρ_{xx}) resistivities in narrow polycrystalline silicon-gated Si(100) field-effect transistors have been obtained. The measurements were carried out both with and without externally applied uniaxial stress. Analysis of the results suggests the presence of large compressive intrinsic edge stresses. A model based on device fabrication is developed to explain the presence of these edge stresses.

7) **Negative magnetoresistance in uniaxially stressed Si(100) inversion layers**

N. Paquin and M. Pepper
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A. Gundlach and A. Ruthven
Edinburgh Microfabrication Facility, King's Buildings, Edinburgh EH9 3JL, United Kingdom
(Received 24 March 1988)

We have studied the negative magnetoresistance of a two-dimensional electron gas in uniaxially stressed Si(100) metal-oxide-semiconductor transistors. The decrease in the fitting parameter α, which is qualitatively explained on the basis of electron-electron interactions, suggests the presence of strong intervalley scattering between heavy- and light-mass subbands. The temperature dependence of τ_{in} supports the modification of the Landau-Baber scattering term in the presence of significant disorder.

8)

Electron Magnetotransport in Uniaxially Stressed Si (100) Inversion Layers

N Paquin and M Pepper
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A Gundlach and A Ruthven
Edinburgh Microfabrication Facility, King's Buildings, Edinburgh EH9 3JL, U.K.

Abstract

The transverse conductivity, σ_{xx}, of uniaxially stressed Si(100) inversion layers has been measured T = 0.36K. The initial application of uniaxial stress leads to an increase in valley-splitting and a reduction of conductivity maxima. At high stresses, on the other hand, conductivity peaks were observed to increase and to merge with increasing stress. At intermediate stresses, the conductivity peak movements can be explained by assuming the presence of a subband-subband electron exchange interaction.

9)

Experimental Determination of Large Intrinsic Edge Stresses in Narrow Silicon Structures

N Paquin, D M Pooke and M Pepper
Cavendish Laboratory, Madingley Road, Cambridge CB3 OHE, United Kingdom
A Gundlach and A Ruthven
Edinburgh Microfabrication Facility, the King's Buildings, Edinburgh EH9 3JL, United Kingdom

Abstract

Piezoresistance measurements have been obtained on narrow polycrystalline silicon-gated silicon field effect transistors. From the anomalous structure observed in the piezoresistance traces it has been deduced that large compressive intrinsic edge stresses are present in these devices. These are estimated from the experimental data to be approximately 180N/mm.^{2}, in reasonable agreement with a theoretical calculation based on a model proposed to explain the presence of such large stresses.

10)

Temperature dependence of the conductivity in uniaxially stressed Si inversion layers at low temperatures

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Edinburgh Microfabrication Facility, The King's Building, Edinburgh EH9 3JL, United Kingdom

Abstract

The temperature dependence of the conductivity in uniaxially stressed Si(100) metal-oxide-semiconductor field effect transistor inversion layers in the weakly localised regime has been measured for temperatures from 1.2K to 4.2K. The results show a strong linear increase in conductivity with decreasing temperature. The application of uniaxial stress is shown to increase or decrease the percentage change in conductivity over the temperature range depending on the initial Fermi level at zero stress.

11)

Electron-Electron scattering in narrow Si accumulation layers

D M Pooke*, N Paquin and M Pepper
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Abstract

We report on measurements of the phase coherence time, τ_0, as determined from the measurement of weak negative magnetoresistance in narrow pinched Si accumulation layers. Under favourable bias conditions, one-dimensional quantum interference and electron interaction corrections to the conductivity are found. The phase coherence length is best described in terms of the Nyquist phase